Evaluating effect of foliage on link reliability of wireless signal

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***Abstract*— Applications of low cost wireless sensor nodes in precision agriculture are being gradually adopted by commercial agricultural cooperatives as part of the continuing industrialisation of commercial agriculture. Current applications require extensive testing and experimentation to ensure reliable message transmission, because the transmitted wireless signal is scattered by the surrounding foliage. Network topology and node density is not optimized. In this paper, experiments to determine the effect of surrounding vegetation on the wireless signal in terms of link reliability, and signal strength for three different types of agricultural crops, namely, ground foliage, medium height and density vegetation, and very dense types of foliage is analyzed and discussed. The objective is to demonstrate that current radio propagation foliage loss models are not optimised for use in precision agriculture.**

Keywords-wireless sensor networks, precision agriculture, scattering, link reliability, distance.

I. Introduction

Historical attempts to improve agricultural yield has focused on increasing output by increasing use of fertilizers and pesticides and automation of irrigation systems. Previously, a large farming area was treated as a homogeneous field in terms of its resource distribution, and its response to variations in climate, weeds and pests [1]. It has become evident that a large field presents wide spatial diversity in soil types, nutrient content, and moisture levels etc. Precision farming techniques focus on optimising the use of water, fertilizers and pesticides to improve agricultural outputs with minimum negative impact on the environment.

Precision agriculture applies technological concepts from various sciences, including, agronomy, computer-, communication- and environmental engineering, to optimally manage spatial and temporal variability in soil and crop ecosystems in order to increase long-term quality and yield of farm products while reducing the negative effects on the surrounding flora and fauna [2, 3, 4, 5].

One of the tools used in precision agriculture are sensors to obtain measurements about humidity, wind, soil and air temperature as well as to efficiently manage water resources by measuring soil moisture. These sensor nodes are standalone devices located close to the phenomena they are observing. Sensors can also be used for early frost and pest detection systems. If threats to optimum growth are detected early enough it is possible to apply the correct pesticide to treat the disease before it spreads out-of-control.

Examples of current usage of sensors in precision agriculture are as yield monitors that use mass flow and moisture sensors to measure the mass or volume of grain flow; yield mapping which combines GPS and yield monitors to obtain more accurate location information of sensor data; variable rate fertilisation to manage application of liquid and gaseous fertilizers, weed mapping and variable spraying to obtain locations of weeds to determine the location and amount of herbicide to apply; salinity mapping to track changes in salinity over time; topography and boundaries to enhance interpretation of yield and weed maps; and guidance systems for seeding, spraying and field scouting [1].

Sensor nodes can wirelessly communicate with each other and/or with a mobile data collector to transmit real-time information about the current state of the plant, soil and weather. This data can be analysed to optimise yield, and water usage, and reduce the use of fertilisers, pesticides and other potentially toxic chemicals. A large number of these sensors deployed across an application area so that each sensor is within radio range of at least one or more other sensors create a Wireless Sensor Network (WSN).

To increase the use of WSNs amongst both large and small-scale farmers, the topology design and deployment of sensor nodes should become easily configurable so that a non-technical person could easily deploy a WSN within an agricultural application area. One of the stumbling blocks preventing rapid adoption of WSN technologies in agriculture is that placement of nodes is dependent on experimentation and as signal strength fades, additional nodes are installed.

Precision agricultural applications require the placement of wireless sensor nodes at or near the flora being monitored. The propagated radio signals are modified by surrounding vegetation, especially due to the presence of water inside the leaves and stalks, causing delay, deviation (diffraction), or absorption (attenuation) of signal strength [6, 7].

Various attenuation models have focused on trees, and do not consider vegetation density. Examples of current models include Weissberger's modified exponential decay model, ITU Recommendation (ITU-R) and the COST 235 model [8]. Models are required that take into consideration the different types of foliage prevalent in agriculture so that a relatively non-technical person could determine the optimum number and deployment location of nodes within an agricultural area.

This paper analyses the effects of vegetation on wireless communication in terms of link reliability, signal strength and distance between transmitter and receiver on three different types of agricultural crops, namely, ground foliage such as strawberries, medium height crops such as peas or potatoes and large height dense fields such as maize. The different range requirements are analysed and discussed. The rest of the paper is structured as follows. In Section II, related work in the precision agriculture field is reviewed. In Section III, the experimental setup is described. Section IV provides a brief summary of two current foliage loss models. In Section V, the results of the experiments are analysed and Section VI provides a conclusion and discusses future work.

II. RELATED WORK

A large number of published articles have focused on applications of WSNs in agriculture, to determine temperature variations, frost damage prevention, irrigation control, and disease management.

In these applications, the actual effect of the surrounding foliage on the wireless signal was not evaluated. If the wireless signal was weaker due to flowering of the plant, the number of sensor nodes within the application area was increased. For example, Beckwith et al [9] deployed a dense 65 node, multi-hop WSN over 2 acres, to measure temperature variations over one management block of a wine vineyard. The authors state that sensors have to be densely deployed to obtain adequate readings of variations in temperature over the application area. In the article it is stated that for a vineyard, nodes were placed 20 to 25 meters apart. Even with this short range, data was only received in 77% of the cases and each piece of data was sent five times to ensure that messages were received. Baggio [10] created a 150 node WSN to monitor phytophthora, a fungal disease, in a potato field. He noted that the radio range performance of the nodes decreased substantially when the potato crop was flowering. To ensure wireless network connectivity, 30 additional relaying nodes were deployed. These relaying nodes were installed at a height of 75 cm to enhance communication, while the sensing nodes were installed at a height of 20, 40 and 60 cm.

The effect of surrounding vegetation on the wireless signal has primarily been researched to determine the growth stage and yield level of the crop. Vegetation scatter models using microwave radar signals to identify moisture in plants and grains have been developed to quantify relations between radiometric observations and vegetation parameters, like leaf area index (LAI), biomass, plant water content, etc. [6].

For example, Fung [7] developed a vegetation scatter model for interpreting scattering from a plane vegetation layer. He demonstrated that layer effects increases with a decrease in volume ratio, depth of layer, plant moisture, and, in general, on the incidence angle of the surrounding foliage. Fung determined that a successful vegetation scatter model could not be established without an adequate permittivity model which properly describes the variations of the permittivity as a function of moisture, frequency and leaf density.

Koay et al. [11] describe a theoretical model developed for paddy fields based on the radiative transfer theory applied to a dense discrete random medium with consideration given to the coherent effects and near-field effects of closely packed scatterers.

The Fung and Koay papers are focused on microwave remote sensing using spaceborne radars and sensors to monitor growth and predict yield with a reasonable accuracy. However, their work can be useful in the WSN application field as there has been a large amount of research done on various scattering models and the effects of soil, moisture and leaf orientation on scattering of electromagnetic waves.

Ndzi et al. [11] evaluated various vegetation attenuation models for frequencies in the range 0.4-7.2 GHz in mango and oil palm plantations. Their observations indicate that greater attenuation is obtained for measurement at canopy height, where there are more branches, twigs and leaves, compared to measurements at trunk heights. The authors suggest placing the nodes above the crop canopy to maximize range. However as the sensors may need to measure soil moisture, humidity and temperature etc., the placement of nodes above the crop canopy may not always be feasible.

III. EXPERIMENTAL SETUP

Measurements were taken for various types of foliage as shown in Table 1.

Vegetation	Height (h)	Typical Types
Ground foliage	0cm < h < 30 cm	Strawberries
Medium foliage	30 < h < 80 cm	Peas, potatoes
Dense foliage	60cm < h< 250cm	Maize, sugarcane

Table 1: Different Vegetation Types evaluated

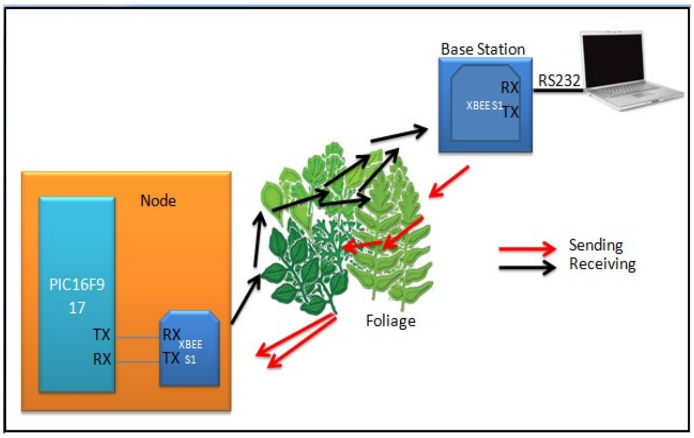

Figure 1: Experimental Setup

Figure 1 shows the experimental setup. The node used in this experiment was composed of a Microchip PIC16F917 and a Xbee S1 XB24-AWB-001 RF transceiver. The XBee modules operate in the ISM 2.4 GHz frequency band. The Xbee Module receiver sensitivity is -92 dBm and the transmit power is 1 mW. The microchip communicates with the Xbee module via UART at 9600 bits per second. The Xbee modules are loaded with the function set XBEE 802.15.4 version 10E6. The Xbee module will execute 3 retries as provided by the 802.15.4 MAC protocol. A standalone XBee node wirelessly connects to another XBee device attached to a laptop.

The sensor nodes were placed in various foliage settings around the University of Johannesburg (UJ) and the Johannesburg Botanical Gardens (JBG), to approximate the various vegetation types. As the experiments were carried out at the end of the winter season in South Africa, various types of vegetation in lieu of actual edible crops were used. For example, in Figure 2, the sensor node was placed amongst some ivy to simulate strawberry type of vegetation and in Figure 8; the sensor node was placed among dense long vegetation to model maize or sugarcane types of vegetation.

The node placed in the foliage runs a loopback algorithm capable of receiving variable size messages from the base station. A message sent by the base station will be read inside the microchip and send back to the base station. The message size can vary from 1 to 80 bits.

Received Signal Strength Indicator (RSSI) measurements and number of correctly received messages versus number of corrupted messages received were evaluated for groups of 50 messages.

IV. THEORETICAL BACKGROUND

The results are compared to the following foliage loss models for the horizontal path [13]. These models are primarily for loss due to scattering from tree foliage of cellular wireless systems.

1. Weissberger model

$$L_w(dB) = 0.45 \times f^{0.284} d \qquad 0m \le d \le 14m$$

Where f is frequency in GHz and d is tree depth in m.

2. ITU-R model

$$L_{ITU-R}(dB) = 0.2 \times f^{0.3} d^{0.6}$$

Where f is frequency in MHz and d is tree depth in m.

Table 2 shows the calculated loss for a frequency of 2.4 GHz.

Distance (m)	Weissberger model	ITU-R model
1	0.577022	2.065824
2	1.154044	3.131204
3	1.731067	3.993614
4	2.308089	4.746018
5	2.885111	5.425945

Table 2: Foliage loss (frequency = 2.4 GHz)

V. RESULTS AND DISCUSSION

The following experiments to determine the effects of different types of foliage on the wireless signal were done. Readings were taken of error-free received messages versus number of messages with errors depending on Received Signal Strength Indicator (RSSI). It was found that a RSSI of -75 dBm provided 100% correct received messages per 50 transmitted messages.

Experiment 1: Place node in ground foliage (ivy at UJ)

Figure 2 shows the transmit node placed within the ivy. A receiver node was placed at the following positions:

- 5.4 m outside foliage from transmit node, with the receiver node placed on ground.
- 5.4 m inside foliage from transmit node, with the receiver node placed on a 13cm box.
- 3 m inside foliage in a straight line from transmit node, with the receiver node placed on ground.
- 3 m inside foliage from transmit node, with the receiver node placed on a 13cm box.

Figure 2: Ground vegetation (ivy)

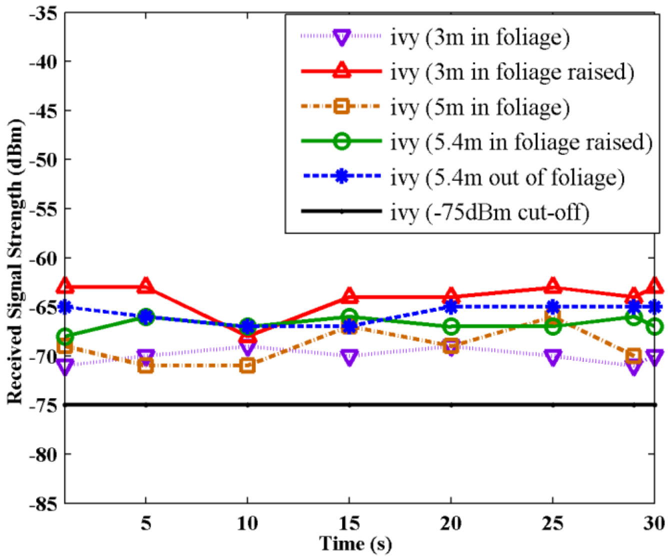

Figure 3: RSSI measurements for short vegetation (ivy)

RSSI readings were measured and are shown in Figure 3. In general, the RSSI for short vegetation does not vary significantly with distance, and all results were above the -75 dBm acceptable range.

The results of the experiments indicate that if the receiver node was slightly raised, for example placed on a small remote controlled car, the received signal would be slightly better than if the node were placed at ground level in the foliage. This is consistent with previous work by Ndzi et al. [11] that showed that range increases when the antenna is placed above the crop canopy. Thus if wireless sensor nodes are to be deployed for a ground cover type agricultural application, less nodes are required and the width of rows can be large and still allow for accurate collection of data.

Experiment 2: Place node in medium height foliage (shrub at JBG)

A transmit node was placed within medium type of vegetation at the JBG as shown in Figure 4. The shrub height is approximately 50-60 cm. A receiver node was placed at the following positions:

- 5 m outside foliage in a straight line from transmitter node. The receiver node was 13 cm above ground.
- 2.4 m outside foliage in a straight line from transmitter node. The receiver node was 13 cm above ground.
- 2.4 m inside foliage from the transmitter node. The receiver node was 13 cm above ground.
- 1.6 m inside foliage from the transmitter node. The receiver node was at ground level.

Figure 4: Medium vegetation (shrub)

RSSI readings were measured and are shown in Figure 5. The maximum distance that two nodes can be placed apart within medium vegetation and ensure 100% correct received messages is 1.6m. If the receiver node is placed outside of the vegetation, the distance and RSSI increases. Typical applications of medium vegetation require the vegetables to be planted in rows, for easier harvesting. Thus, the shorter distances would not negatively impact deployment and reliable collection of data from wireless sensor nodes. A small mobile data collector could easily move along these rows and reliably collect data from static nodes.

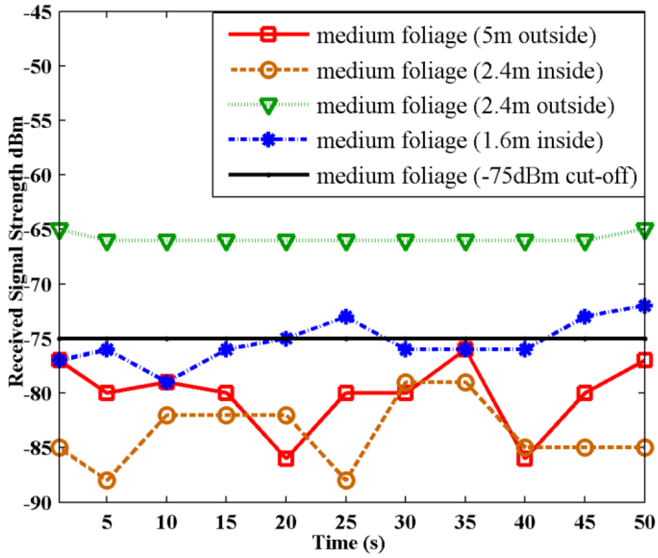

Figure 5: RSSI measurements for medium vegetation (shrub)

Experiment 3: Place node in medium height dense foliage (long dense grass at UJ)

Fig. 6 shows a transmitter node placed within dense, medium type of vegetation at UJ. The dense grass height is approximately 60-80 cm. A receiver node was placed at ground level at the following positions:

- 1 m inside foliage in a straight line from transmit node.
- 2 m inside foliage in a straight line from transmit node.
- 1 m outside foliage in straight line from transmit node.
- 2 m outside foliage in straight line from transmit node.

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Figure 6: Dense vegetation (grass)

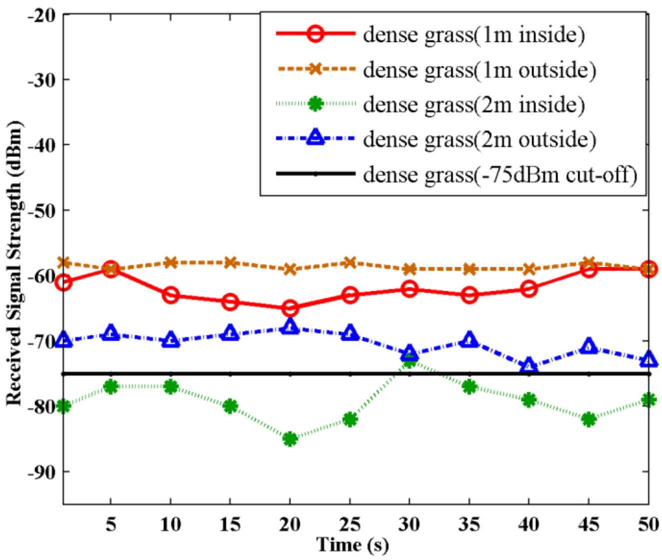

Figure 7: RSSI measurements for medium vegetation (grass)

The RSSI measurements are shown in Figure 7. RSSI strength deteriorates significantly with distance in dense vegetation. To ensure reliable communication between sensor nodes in a dense vegetation application, the nodes will have to be closely spaced. Alternatively, static nodes can be placed at various points within the vegetation and would only be able to communicate with a mobile data collector that could move between rows of vegetation.

Experiment 4: Place node in long height dense foliage (hedge at JBG)

A transmitter node was placed within dense, hedge approximately 2.7m in height with a depth (width) of 3.4m at JBG as shown in Figure 8.

A receiver node approximately 13cm above ground was placed at the following positions:

- 2.4 m inside foliage in a straight line from transmit node.
- 2.0 m inside foliage in a straight line from transmit node.
- 3.0 m inside foliage in a straight line from transmit node.
- 4.0 m inside foliage in a straight line from transmit node.

The RSSI measurements are shown in Figure 9. There is a cut-off point of around 2.4 m after which the RSSI levels decrease and the number of inaccurate received messages increases. At a distance of approximately 4 m, no reliable messages were received. For dense agricultural vegetation, such as maize, the maximum distance static nodes can be placed to ensure effective communication would be around 2.4m. This relationship between the RSSI and the Good/Bad message received ratio is verified in Figure 10.

Figure 8: Dense, long height vegetation (hedge)

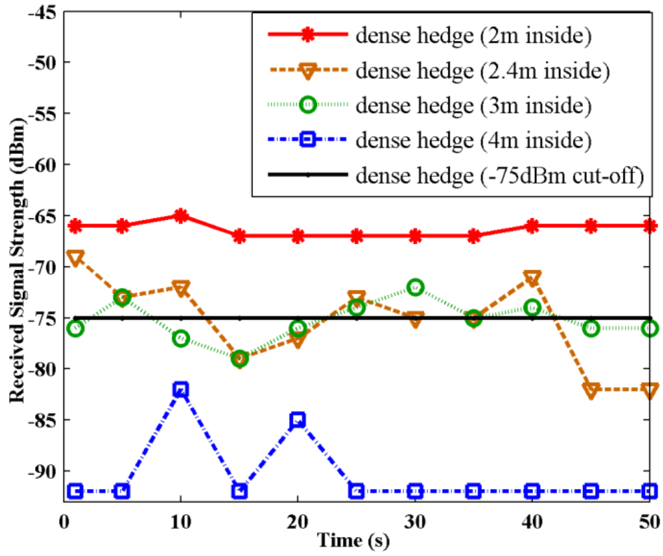

Figure 9: RSSI measurements for long, dense vegetation (hedge)

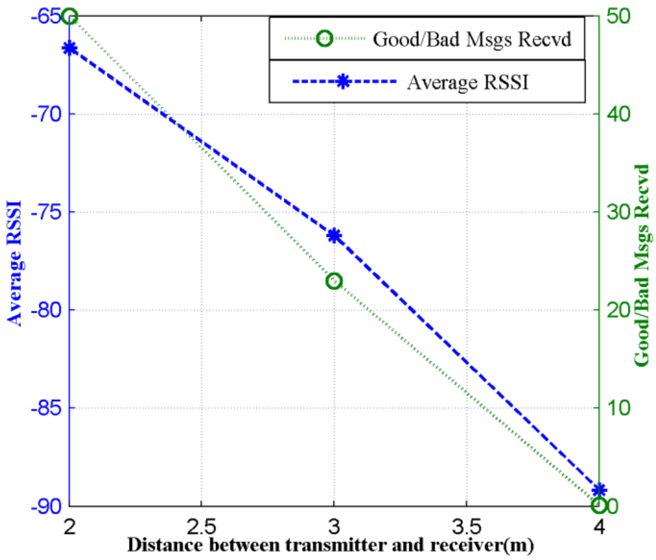

Figure 10: Relationship of Good vs. Bad messages and RSSI to distance

VI. Conclusion

It is evident when the results of Section V is compared with the calculated values from Table 2 (Section IV), that current models to evaluate the effect of foliage on power received are not completely appropriate for use in the application of WSNs in precision agriculture.

Experimental evaluation of the effect of vegetation on the wireless signal strength indicates that a homogenous deployment of sensor nodes within an agricultural area for all types of vegetation is not practically realistic. Cognisance of the height, width, type and density of the vegetation has to be considered in the planning and deployment of a WSN application within an agricultural field. If a model can be developed that can easily allow the user to determine the number and position of nodes to deploy within an agricultural field with respect to the type of foliage, than the large scale adoption of WSNs within the agricultural industry will significantly increase.

In this paper, we have conducted experiments that indicate distances at which nodes have to be placed apart, depending on the type of vegetation being planted (we assume foliage of plant at maturation and ignore the minimum effect on the wireless signal at the seedling stage). These values can be used in an initial deployment of a WSN to ensure greater accuracy of communication and link reliability between nodes.

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